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Patents ADP number *(if you know it)*

~~05814181001~~ 5532072002

If the applicant is a corporate body, give the country/state of its incorporation

N/A

4. Title of the invention

NOVEL WAVEFRONT SENSOR

5. Name of your agent *(if you have one)*

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Novel Wavefront Sensor

1. Background

Adaptive optics (AO) is a technique involving real-time modification of the properties of an optical system based on measured optical output that is indicative of system optical performance. AO systems are now widely used for compensation of turbulence in imaging through turbulent media in astronomical[1] and military[2] applications, for control of laser-beam delivery[3], for control of laser resonator properties[4], for ophthalmic applications[5] and in other areas.

In general AO systems comprise 3 components:

- a wavefront modulator (WFM - which alters the optical properties of the system in response to a command signal)
- a wavefront sensor (WFS - which monitors the difference in state between the desired optical performance and the current optical performance of the system) and
- a control loop (which drives the WFM in response to the output from the WFS).

For control of an adaptive optical system it is not strictly necessary, and may even be detrimental, to reconstruct the input wavefront. A sufficient condition for satisfactory operation of an adaptive optical system is the ability to drive a wavefront modulator using a null sensor, where a control signal derived from a wavefront sensor system indicates the size and, preferably, the location and the direction of the wavefront error. Thus, if the wavefront modulator is providing full correction of the input wavefront error, the control signal will be zero and the wavefront modulator will not be driven from its present position. The simplest example of such systems are based on multi-dither techniques applied, for example[4,6], to the correction of thermal lensing in laser resonators.

Phase-diversity[7] has historically been seen as an algorithm for reconstruction of wavefront phase from data corresponding to images of the input wavefront intensity on two planes normal to the direction of propagation and located at different positions along the axis of propagation. The approach taken is generally close to the 'two-defocus' method used in microscopy[8] and operates with two close-to-focus images[9]. Although the data planes are generally described as symmetrically placed about the image plane, they can equally well be symmetrically placed about the system input pupil[10], in which case the phase diversity algorithm becomes essentially the same as the wavefront curvature algorithm[11].

For measurements on planes symmetrically spaced either side of either the image or the pupil planes, the intensity on the two measurement planes will be identical, and the difference between the images will be zero, if and only if the wavefront in the entrance pupil plane is a plane wavefront. The measurement of the difference between the intensity on the two data planes (the phase-diverse data), thus satisfies the requirements for a null sensor. If the input wavefront is distorted the propagation between the measurement planes results in convergence (concave wavefront) or divergence (convex wavefront) and the resulting intensity difference between the measurement planes is indicative of the location, magnitude and direction of the wavefront curvature. For reconstruction of the wavefront phase the inverse problem

may be solved iteratively[12,13] or presented in terms of the differential Intensity Transport Equation (ITE) and solved through the use of Green's functions[14] with the phase-diverse data providing an estimate of the axial derivative of the intensity. Assumptions imposed through use of the ITE involve uniformity of the input intensity in the entrance pupil, continuity in the wavefront phase and continuity of the first derivative of the wavefront phase[15].

The data on the two image planes is recorded using various approaches, including physical displacement of the image plane[9], use of a vibrating spherically-distorted mirror, beam splitters and folded optical paths, or by the use of off-axis Fresnel lenses[10]. Each of these approaches has its merits and drawbacks, but each corresponds to the recovery of phase information from two data sets recorded under different focus conditions. As such, all of these approaches are related to the two-defocus methods applied in electron microscopy in the 1970s. An alternative description is based on a matched filter approach[16], using a diffractive optical element to provide a pair of spots whose axial intensity (passing through a pinhole) defines the amplitude of each aberration mode in a distorted wavefront.

At the expense of assumptions imposed on the uniformity of the input illumination, the current work on phase-diversity has progressed a long way from the early electron microscope applications of the two-defocus technique and ITE-based approaches have demonstrated real-time data reduction with high (sub-nanometre) accuracy[17]. However, in all cases the two data sets are recorded under conditions where the wavefront is subject to a known defocus aberration between the two measurements.

2. Problem to be solved

The restrictions on the uniformity of the input wavefront mean that current wavefront sensors cannot be used with scintillated, discontinuous, or multiply-connected wavefronts. There are many areas in which a generalised method which can cope with scintillated, discontinuous and off-axis wavefronts would be a great advantage. One example is in polishing machines, where it would be useful to measure *in situ* the surface profile of the object being polished. This would inevitably involve laser illumination of rough surfaces. It would also be useful to be able to image silicon circuitry, which by definition, is highly discontinuous.

3. The Invention

A null sensor is a wavefront sensor that will produce a null output if the input wavefront is a plane wave, but which will return an error signal when the input is distorted. A plane wave is defined as having constant phase across its wavefront. Without loss of generality that phase can be taken to be zero, so that its Fourier transform is Hermitian.

Sufficient conditions for the null sensor are that it should give null output for input with Hermitian symmetry, and that it give non-zero output for non-plane input wavefronts. Necessary conditions are first that the filter function must be complex. If either the real or imaginary part is zero then the sensor will give null output for any input. In addition, mixed symmetries of the real and imaginary parts of the filter function must be avoided. For unambiguous sensor output it is necessary that the real

and imaginary parts have either both odd or both even symmetry. The defocus filter does fulfil these conditions. From these conditions it is possible to construct a null sensor without having placed any limiting assumptions on the input wavefront. This method will therefore be suitable for scintillated and discontinuous input wavefronts.

The invention is a null wavefront sensor consisting of an input wavefront to be corrected and

– an imaging means
– an aberrating means
– a detecting means
– a feedback means,

arranged such that the imaging and detecting means capture images of the wavefront field in a manner such that the wavefront field imaged is subject to two or more different aberrations imposed by the aberrating means. The aberrating means which combined with the imaging means can deliver to the detecting means simultaneously or sequentially images of the input wavefront field subject to different but known aberrations such that the aberration functions have complex odd or complex even symmetry and at least two of the images are subject to aberration functions that are complex conjugate pairs but are not pure defocus aberrations and may or may not be described by any pure Zernike polynomial. An electronic feedback means is arranged to deliver to an adaptive optics wavefront modulator a signal derived from the difference between the images affected by the complex conjugate aberrating means and used to drive the wavefront modulator in such a manner that the feedback signal strength is zero when the images recorded with complex conjugate aberrating means are identical. For the avoidance of doubt, an example of complex conjugate filter pairs could consist of a filter function that produces aberration functions whose optical phase is reversed in arithmetic sign. The use of off-axis Fresnel lenses to produce defocus is such an example[10].

The aberrating function can be a weighted sum of Zernike polynomials arranged optimally to equalise the signal generated from each mode of deformation to be corrected in the input wavefront field according to the expected statistical distribution of such modes in the input wavefront field. The aberrating means can be a diffractive optical element arranged such that the complex conjugate aberration functions are associated with diffraction orders of the same order but different sign (±1, ±2, etc). Alternatively, the aberrating means can be a variable-shape optical mirror or a variable refractive index device such as a liquid crystal phase modulator used sequentailly to provide complex conjugate aberrations. The aberrating means can also consist of a deformed reflective surface where the illumination of that surface from each side produces the complex conjugate aberration functions.

The following sections show that these aberration functions are capable of encoding the sense and location of wavefront errors on heavily scintillated and discontinuous input wavefronts. The necessary and sufficient conditions required of aberration functions suitable for use in a generalised phase-diversity null wavefront sensor for adaptive optics applications are quantified.

3.1 Analysis

Let $\Psi(r)=|\Psi(r)|e^{i\varphi(r)}$ represent the complex amplitude distribution in the entrance pupil of an optical system, r being the co-ordinate in the pupil plane. If $\Psi(r)$ represents a plane wavefront, the phase satisfies $\varphi(r)=\text{constant}$. Any spatial variation in the wavefront phase represents a distortion, or aberration, that requires correction in an AO system.

To operate successfully as a null wavefront sensor in an AO system we require a device that produces an error signal if, and only if, $\varphi(r)$ is not constant⁺. It is desirable that the error signal provides information that localises the wavefront error in r-space and indicates the sense in which correction should be effected (in the absence of such indication a multi-dither technique[18] is required to effect correction).

Let $\psi(\xi)=H(\xi)+A(\xi)$ be the Fourier transform of $\Psi(r)$, where $H(\xi)$ and $A(\xi)$ represent respectively the Fourier transforms of the real and imaginary parts of $\psi(\xi)$. Clearly, $H(\xi)$ is Hemitian and $A(\xi)$ is anti-Hermitian. These symmetry properties will be required later. Thus,

$$\begin{aligned} H(\xi) &= H^*(-\xi) \\ A(\xi) &= -A^*(-\xi) \end{aligned} \tag{1}$$

Let $F_\pm(\xi)=R(\xi)\pm iI(\xi)$ be the Fourier transform of a filter function $f_\pm(r)$, which represents a complex function with which $\Psi(r)$ is convolved when forming an image of the system entrance pupil. The functions $R(\xi)$ and $I(\xi)$ are real-valued functions and the $\pm$ indicates the use of two filter functions, in which the Fourier phase of the filter is reversed. In this work we are particularly interested in the necessary and sufficient conditions that constrain $R(\xi)$ and $I(\xi)$ in such a way that $f_\pm(r)$ are suitable filter functions to provide a null wavefront sensor for use in adaptive optics.

The physical relationship between these different functions is indicated schematically in figure 1.

The detected intensity function may thus be written

$$j_\pm(r)=\left|\int d\xi\, \psi(\xi)F_\pm(\xi)e^{-i\xi\cdot r}\right|^2. \tag{2}$$

Substituting for $F_\pm$, expanding and simplifying, the difference between the images formed using the two filter functions may be expressed

⁺ We will consider the optical output from monochromatic systems here. Thus a discontinuity of exactly an integral number of wavelengths in size does not affect the optical output, eg. image intensity profile, and may be regarded as an undistorted wavefront. Such a discontinuity becomes a potentially-important wavefront error in metrology applications.

$$d(r) = j_+(r) - j_-(r)$$
$$= 2i[\int d\xi\ \psi(\xi)I(\xi)e^{-ir\xi} \int d\xi'\ \psi^*(\xi')R(\xi')e^{ir\xi'}$$
$$- \int d\xi\ \psi(\xi)R(\xi)e^{-ir\xi} \int d\xi'\ \psi^*(\xi')I(\xi')e^{ir\xi'}] \quad (3)$$

This is a real-valued function, since the quantity in [ ] is a difference of two complex conjugates and is thus imaginary-valued, so

$$\frac{d(r)}{2i} = \int d\xi[H(\xi)+A(\xi)]I(\xi)e^{-ir\xi} \int d\xi'[H^*(\xi')+A^*(\xi')]R(\xi')e^{ir\xi'}$$
$$- \int d\xi[H(\xi)+A(\xi)]R(\xi)e^{-ir\xi} \int d\xi'[H^*(\xi')+A^*(\xi')]I(\xi')e^{ir\xi'}. \quad (4)$$

The rhs of (4) can then be expanded and the terms grouped into 4 separate expressions which are equal to the rhs of (4) when summed:

$$\int d\xi H(\xi)I(\xi)e^{-ir\xi} \int d\xi' H^*(\xi')R(\xi')e^{ir\xi'} - \int d\xi H(\xi)R(\xi)e^{-ir\xi} \int d\xi' H^*(\xi')I(\xi')e^{ir\xi'} \quad (5.1)$$

$$\int d\xi H(\xi)I(\xi)e^{-ir\xi} \int d\xi' A^*(\xi')R(\xi')e^{ir\xi'} - \int d\xi A(\xi)R(\xi)e^{-ir\xi} \int d\xi' H^*(\xi')I(\xi')e^{ir\xi'} \quad (5.2)$$

$$\int d\xi A(\xi)I(\xi)e^{-ir\xi} \int d\xi' H^*(\xi')R(\xi')e^{ir\xi'} - \int d\xi H(\xi)R(\xi)e^{-ir\xi} \int d\xi' A^*(\xi')I(\xi')e^{ir\xi'} \quad (5.3)$$

$$\int d\xi A(\xi)I(\xi)e^{-ir\xi} \int d\xi' A^*(\xi')R(\xi')e^{ir\xi'} - \int d\xi A(\xi)R(\xi)e^{-ir\xi} \int d\xi' A^*(\xi')I(\xi')e^{ir\xi'} \quad (5.4)$$

This expression for the difference between the two detected intensity functions is generally valid – no restricting assumptions have so far been made. We may now investigate under what conditions of symmetry these expressions individually, or summed, are identically zero.

3.2 Conditions for operation as a null wavefront sensor

3.2.1 Filter function must be complex

Unless both R and I are non-zero, all of the terms in equations (5) are identically zero $\forall \psi$. Thus $d(r)$ is identically zero for all input wavefronts and no error signal is generated from a non-flat wavefront.

This may be readily understood since if the filter function is purely real the filter function $F_\pm$ is identical whatever the arithmetic sign, so the two images are identical. If the filter is purely imaginary the change of arithmetic sign is lost by the modulus square operation that is an inevitable part of quadrature detection processes – and thus the two images are again identical.

3.2.2 Complex filter function

3.2.2.1 Even symmetry

Suppose that both $I(\xi)$ and $R(\xi)$ are even functions of ξ.

Consider the first expression (5.1). Since $H(\xi)$ is Hermitian and $I(\xi)$ is symmetric and real-valued the product $H(\xi)I(\xi)$ is Hermitian. Thus the Fourier integral $\int d\xi H(\xi)I(\xi)e^{-ir.\xi}$ is real-valued. The same is true of $\int d\xi' H^*(\xi')R(\xi')e^{ir.\xi'}$. The second product of two integrals is term by term the complex conjugate of the first product. Thus expression (5.1), the difference between two complex conjugates, is always zero when both $I(\xi)$ and $R(\xi)$ are symmetric.

Similarly (5.4) is always zero because each of the integrals reduces to a purely imaginary function. The product of these imaginary functions is real and the difference between the two complex conjugate terms is again always zero.

Thus the difference between the two images is the sum of (5.2) and (5.3) and can be written

$$\frac{d(r)}{2i} = \int d\xi H(\xi)I(\xi)e^{-ir.\xi} \int d\xi' A^*(\xi')R(\xi')e^{ir.\xi'} - \int d\xi A(\xi)R(\xi)e^{-ir.\xi} \int d\xi' H^*(\xi')I(\xi')e^{ir.\xi'}$$
$$+ \int d\xi A(\xi)I(\xi)e^{-ir.\xi} \int d\xi' H^*(\xi')R(\xi')e^{ir.\xi'} - \int d\xi H(\xi)R(\xi)e^{-ir.\xi} \int d\xi' A^*(\xi')I(\xi')e^{ir.\xi'} \quad (6)$$

In equation (6), for each pair of integrals one integral reduces to a real-valued function and the other integral to an imaginary-valued function. The first and second terms, also the third and fourth terms, are complex conjugate pairs and thus the rhs of (6) is imaginary valued or zero.

If either H or A is zero or if $A = He^{i\varphi}$ with φ constant, equation (6) and thus $d(r)$, is zero. However, these conditions are exactly those under with the input wavefront is flat and a null sensor is required to produce a null output.

Thus, if the filter function is complex with even symmetry the difference between the two images formed using these filters forms a potentially-useful null wavefront sensor.

3.2.2.2 Odd symmetry

Suppose that both $I(\xi)$ and $R(\xi)$ are odd functions of ξ.

In (5.1) and in (5.4) the odd symmetry of the real functions R and I means that the products within the integrals in (5.1) have anti-Hermitian symmetry and those within (5.4) have Hermitian symmetry. Thus, although the arguments given are reversed for each term from those given in 3.2.1, both (5.1) and (5.4) are identically zero $\forall\psi$. Thus $d(r)$ again reduces to equation (6). The arguments from 3.2.1 again hold, although the role of the terms is reversed, one term in each integral product is purely real and the other term purely imaginary.

Thus a filter function with complex odd symmetry is potentially suitable for use as a filter function for wavefront sensing.

3.2.2.3 Mixed symmetry

Suppose that one of $I(\xi)$ and $R(\xi)$ is an even function of ξ and the other is an odd functions of ξ.

In (5.1) the mixed symmetry will result in one of the integrals in each product being purely imaginary and the other integral purely real (dependent on whether I or R is odd). In either case the product of the integrals is purely imaginary and thus (5.1) is purely imaginary or zero. An equivalent argument shows that (5.4) is purely imaginary or zero.

Note, however, that the expressions (5.1) and (5.4) are reliant on the interactions between H and the filter function or on A and the filter function and do not involve cross terms between H and A.

In equation (6) the mixture of odd and even symmetry will mean that both integrals in each product are either purely real or purely imaginary. In each case the product of these terms will be purely real and the difference of the complex conjugates will thus be zero $\forall \psi$.

Thus, filters with mixed symmetry produce no error signal dependent on the deviation of the wavefront from a plane wave and thus such filters are unsuitable for use as a wavefront sensor.

3.2.3 Sensing the error direction

We have established that the crucial term that encodes information about the wavefront aberrations is the sum of the cross terms in equation (6).

If the sense of the wavefront error is reversed, the phase of the wavefront will change arithmetic sign. This means that for a wavefront error of a given amplitude the error signal (equation (6) for filter functions with complex even or complex odd symmetry) changes sign if the sense of the error is reversed. The wavefront sensor thus delivers an error signal that preserves information about the sense of the wavefront error.

Note that, since the relationship between the error signal and the wavefront error is non-linear (involving the balance between H and A in the description of the wavefront), this does not guarantee that the error signal can be inverted to find the wavefront shape.

3.2.4 Localising the wavefront error

Returning to equation (6) we note that each of the integrals, when expressed as a function of r appears in the form of a convolution of H or A with a real-valued function deriving from the filter function. As the products are of complex functions

and real-valued function the phase of the product is identically equal to that of the Hermitian or Anti-Hermitian function in each integral.

Without loss of generality, the location of the wavefront error can be identified with the position at which $a(r)$, the Fourier transform of $A(\xi)$, is non-zero. Because no phase ramp is added by the product with the real-valued filter function, the location of the non-zero component is, in some sense, localised at the point where $a(r)$ is non-zero.

3.3 Implementation

The requisite filter functions could be implemented in several ways, but one of the most straightforward approaches (for use with quasi-monochromatic radiation) is to use a diffractive optical element (DOE) to introduce the aberration.

This scheme exploits the phase detour effect to implement the complex conjugate aberration functions in a manner similar to that used in the two-defocus implementation[19] whereby the requisite phase distribution for the aberrating filter function is encoded in a computer-generated phase hologram. Implementation diagrams shown for the use of the filters defined here would appear as in Figure 1, in which the dashed line (1) represents a DOE used to implement the requisite filter functions in the $\pm$ diffraction orders and the zero order contains an image of the field to be reconstructed. In situations where the photometric efficiency is important a phase grating may be used and the depth of the grating adjusted to reduce to zero, or close to zero, the flux in the zero diffraction order. In Figure 1, (1) represents the positioning of the DOE that is used to generate the aberrations, (2) represents the image with aberration function $j_+(r)$, (3) represents the image with aberration function $j_-(r)$, (4) represents the wavefront to be reconstructed, and (5) represents the image of the wavefront to be reconstructed.

Figure 2 shows the combination of DOE (diffraction grating) with SLM (spatial line modulator – operated using liquid crystals) wavefront modulators to produce an adaptive optical system driven using a null sensor.. In Figure 2 (6) represents the CMOS (complementary metal oxide semiconductor) camera, (7) represents the lens, (8) represents the diffraction grating, and (9) represents the SLM's (spatial line modulators – operated using liquid crystals). The difference between the two images on a pixel by pixel basis is used directly to drive the wavefront modulators in order to provide the requisite wavefront correction. Because the difference between the images is zero when the system has diffraction-limited performance the wavefront sensor provides no correction signal if the system is diffraction limited.

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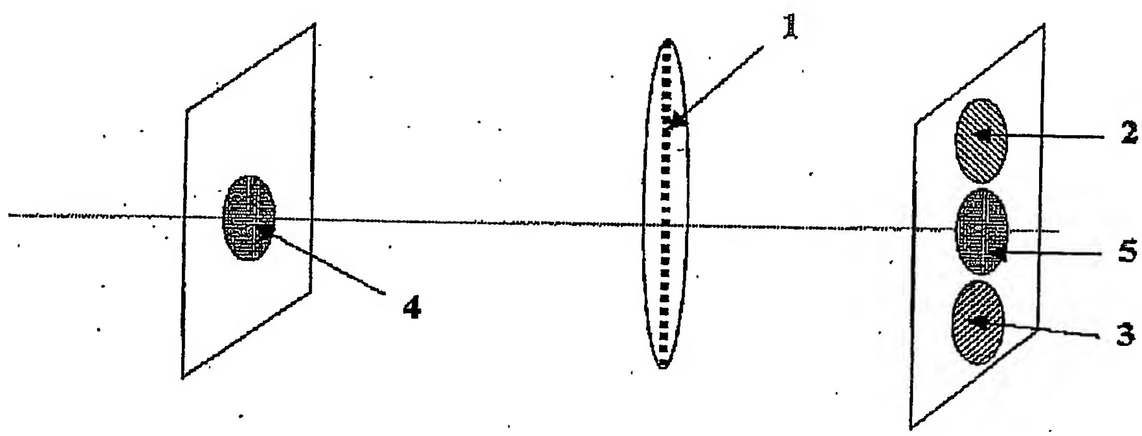

Figure 1

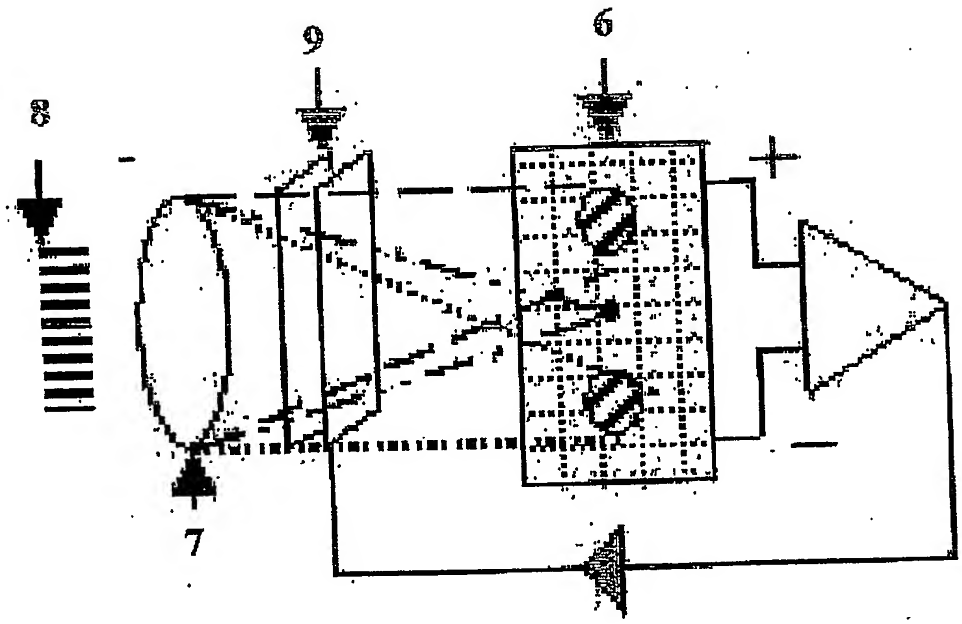

Figure 2